The Flavor and Spin Structure of Hyperons from Quark Fragmentation

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Abstract

We systematically study the hadron longitudinal polarizations of the octet baryons at large z from quark fragmentations in e^+e^--annihilation, polarized charged lepton deep inelastic scattering (DIS) process, and neutrino (antineutrino) DIS process, based on predictions of quark distributions for the octet baryons in the SU(6) quark-spectator-diquark model and a perturbative QCD based counting rule analysis. We show that the e^+e^--annihilation and polarized charged lepton DIS process are able

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to distinguish between the two different predictions of the hyperon polarizations. We also find that the neutrino/antineutrino DIS process is ideal in order to study both the valence content of the hyperons and the antiquark to hyperon (quark to anti-hyperon) fragmentations, which might be related to the sea content of hyperons.

1 Introduction

Recently there have been some significant progress in understanding the flavor and spin structure of the Λ-hyperon from various fragmentation processes, both theoretically [1-18] and experimentally [19-24]. One of the most interesting new observations is related to the polarizations of the up (u) and down (d) quarks inside the Λ. In the naive quark model, the Λ spin is totally provided by the strange (s) quark, and the u and d quarks are unpolarized. Based on novel results concerning the proton spin structure from deep inelastic scattering (DIS) experiments and SU(3) symmetry between the octet baryons, it was found that the u and d quarks of the Λ should be negatively polarized [2]. It was also pointed out that the u and d polarizations in the Λ are related to the s polarizations of the proton [9]. However, based on a perturbative QCD (pQCD) counting rule analysis [25, 26] and an SU(6) quark-spectator-diquark model [27], it was later predicted [10, 11, 16] that, although the u and d quarks of the Λ might be unpolarized or negatively polarized in the integrated Bjorken range $0 \leq x \leq 1$, they should be positively polarized at large x. This prediction seems to be supported by all available data from longitudinally polarized Λ fragmentations in e^+e^--annihilation [19, 20, 21], polarized charged lepton DIS process [22, 23], and most recently, neutrino (antineutrino) DIS process [24].

However, there are still many unknowns to be explored before we can arrive at some definite conclusion on the Λ quark and spin structure. First, what one actually measures in experiments are the hyperons from quark fragmentation, and therefore one needs a relation between quark distributions and fragmentation functions. The Gribov-Lipatov relation [28, 29]

$$D_q^h(z) \sim z \, q_h(z) \ , \tag{1}$$

with $D_q^h(z)$ being the fragmentation function for a quark q splitting into a hadron h with longitudinal momentum fraction z, and $q_h(z)$ being the quark distribution of finding the quark q inside the hadron h carrying a momentum fraction $x = z$, was used to connect the fragmentation functions from predictions on the quark distributions [10, 11, 12, 16, 17, 29]. However, such a relation is only known to be valid near

$z \to 1$ and on a certain energy scale Q_0^2 in leading order approximation, and there are serious doubts, coming from both theory and experiment, as to whether this relation can be applied anywhere else. Thus it might be more practical to consider Eq. (1) as a phenomenological Ansatz to parameterize the quark to Λ fragmentation functions, and then check the validity and reasonableness of the method by comparing the theoretical predictions with the experimental data. In fact, most other theoretical estimates [2, 5, 7, 8, 15, 18] on the quark fragmentation functions are also based on some knowledge of quark distributions. Second, there are still uncertainties on the quark distributions, even for the valence components. For example, the flavor structure of the Λ differs significantly in the pQCD based analysis and the quark-diquark model: the ratio $u(x)/s(x)$ at $x = 1$ is 1/2 in the pQCD analysis whereas it is 0 in the quark-diquark model [10]. But the two models have similar predictions of the Λ polarizations of fragmentations in e^+e^--annihilation [11], polarized charged lepton DIS process [10, 16], and neutrino (antineutrino) process [16], and it is still difficult to distinguish between the two different model predictions with the available data. Therefore we still need to look for new quantities and kinematic regions where the distinction of the different predictions is feasible.

It has been pointed out [12] that the two different predictions of the quark distributions for the $\Sigma^\pm$ and Ξ^- hyperons can be directly tested in Drell-Yan processes of charged hyperon beams on the nucleon target. However, it might take a long time for performing such experiments, since the technique on the charged hyperon beams still needs improvement for precision experimental purposes. By comparison, the detection technique of Σ and Ξ hyperons is more mature in order to measure the various quark to hyperon fragmentation functions [30, 31, 32]. Except for the Σ^0, which decays electromagnetically, all other hyperons in the octet baryons have their major decay modes mediated by the weak interaction. Because these weak decays do not conserve parity, information from their decay products can be used to determine their polarization [30, 31]. The polarization of Σ^0 can be also re-constructed from the dominant decay chain $\Sigma^0 \to \Lambda\gamma$ and $\Lambda \to p\pi^-$ [32]. Therefore we can use the measurable fragmentation functions to extract information on the spin and flavor content of hyperons with the available experimental facilities. From another point of

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view, studying the fragmentation functions of various hyperons is also interesting in itself, in addition to its connection to the quark distributions. The purpose of this paper is to study the longitudinal polarizations of various hyperon fragmentations in e^+e^--annihilation, charged lepton DIS process, and neutrino DIS process, based on predictions of quark distributions for the hyperons in the pQCD analysis and quark-diquark model. This is useful as a systematically survey of various hyperon fragmentation functions, as well as checking different model predictions.

The paper is organized as follows. In Sec. II we will present a brief review of the quark distributions for the octet baryons in both the quark-diquark model and the pQCD based analysis. For the pQCD based analysis we make a new set of leading order quark distributions for the valence quarks with SU(3) symmetry between the octet baryons. This set of quark distributions has no other free parameters, therefore it has predictive ability. In Sec. III we calculate the baryon polarizations in e^+e^--annihilation for the octet baryons at two energies: LEP I at the Z resonance $\sqrt{s} \approx 91$ GeV and LEP II at $\sqrt{s} \approx 200$ GeV. We find that predicted polarizations for Σ's are quite different in the two models in the medium to large z region, and a distinction between different predictions can be checked by measuring the $\Sigma^{\pm}$ polarizations in e^+e^--annihilation. Sec. IV contains our predictions for the baryon and anti-baryon polarizations of the octet baryons in polarized charged lepton DIS process. We find that the Ξ^0 has the biggest difference for the spin transfer in the two different models, and we propose to measure the Ξ^0 polarization in this process as a sensitive test of different predictions. Sec. V is devoted to the baryon and anti-baryon polarizations of the octet baryons in neutrino (antineutrino) DIS process. We find that the neutrino (antineutrino) DIS process is ideal to test different predictions concerning both the valence and sea content of the hyperons. Finally, we present a summary of our new results together with our conclusions in Sec. VI.

2 The quark flavor and spin structure of octet baryons

The valence quark distributions of the octet baryons, in both the light-cone SU(6) quark-spectator-diquark model [27] and the pQCD based counting rule analysis [26], have been discussed in previous publications [10, 11, 12]. Here we briefly outline the main ingredients and new features that are present in this paper for the later applications.

2.1 The light-cone SU(6) quark-spectator-diquark model

The application of the quark-spectator-diquark model to discuss the quark distributions of nucleons at large x can be traced back to a work of Feynman, to explain the unexpected behavior of $F_2^n(x)/F_2^p(x) = 1/4$ at $x \to 1$ in the experimental observation at that time [33]. There have been many developments along this line [34], and the light-cone SU(6) quark-spectator-diquark model [27] is a revised version with the new ingredient of Wigner-Melosh rotation effect [35, 36] taken into account. This model does not necessarily break the bulk SU(6) symmetry of the wavefunction, and is successful in describing the large x behavior of polarized structure functions of nucleons. The main idea of this model is to start from the three quark SU(6) quark model wavefunction of the baryon and then if any one of the quarks is probed, reorganize the other two quarks in terms of two quark wavefunctions with spins 0 or 1 (scalar and vector diquarks), i.e., the diquark serves as an effective particle which is called the spectator. The advantage of this model is that the non-perturbative effects such as gluon exchanges between the two spectator quarks or other non-perturbative gluon effects in the hadronic debris can be effectively taken into account by the mass *et al.* of the diquark spectator. So the complicated many-particle system can be effectively treated by a simple two particle system technique [37, 38]. The mass difference between the scalar and vector diquarks is proved to be important for producing consistency with experimental observations [27], in comparison with the naive quark model with exact SU(6) symmetry.

The light-cone SU(6) quark-spectator-diquark model [27] is extended to the Λ-hyperon in Refs. [10, 11]. It is interesting to notice that the mass difference between the scalar and vector diquarks causes a suppression of anti-parallel spin components of quark distributions at large x, and as a consequence the totally non-polarized u and d quarks should be positively polarized at large x. Surprisingly, the predictions of the model with naive parameters, and without any adjustment, have been proved to be successful in describing all of the available data of Λ polarizations in e^+e^--annihilation [11], polarized charged lepton DIS process [10, 16], and neutrino (antineutrino) DIS process [16], by adopting the simple Ansatz of the Gribov-Lipatov relation Eq. (1), in order to connect fragmentation functions with distribution functions. It is natural that we should try to check or refine the validity of this method by exploring hadron fragmentations of other octet baryons. The extension of the light-cone SU(6) quark-spectator-diquark model to the octet baryons has been done in Ref. [12], and we outline the main ingredients in the following.

The unpolarized quark distribution for a quark with flavor q inside a hadron h is expressed as

$$q(x) = c_q^S a_S(x) + c_q^V a_V(x), \qquad (2)$$

where c_q^S and c_q^V are the weight coefficients determined by the SU(6) quark-diquark model wavefunctions and are different for various baryons, and $a_D(x)$ ($D = S$ for scalar spectator or V for axial vector spectator) can be expressed in terms of the light-cone momentum space wavefunction $\varphi(x, \mathbf{k}_\perp)$ as

$$a_D(x) \propto \int [\mathrm{d}^2 \mathbf{k}_\perp] |\varphi(\mathrm{x}, \mathbf{k}_\perp)|^2 \qquad (D = \mathrm{S \ or \ V}) \qquad (3)$$

which is normalized such that $\int_0^1 \mathrm{d}x a_D(x) = 3$ and denotes the amplitude for quark q to be scattered while the spectator is in the diquark state D. We employ the Brodsky-Huang-Lepage (BHL) prescription [37] of the light-cone momentum space wavefunction for the quark-diquark

$$\varphi(x, \mathbf{k}_\perp) = A_D \exp\{-\frac{1}{8\alpha_D^2}[\frac{m_q^2 + \mathbf{k}_\perp^2}{x} + \frac{m_D^2 + \mathbf{k}_\perp^2}{1-x}]\}, \qquad (4)$$

with the parameter $\alpha_D = 330$ MeV. Other parameters such as the quark mass m_q,

vector(scalar) diquark mass m_D ($D = S, V$) for the octet baryons are listed in Table 1.

One needs to introduce the Melosh-Wigner correction factor [35, 36] in order to calculate the polarized quark distributions

$$\Delta q(x) = \tilde{c}_q^S \tilde{a}_S(x) + \tilde{c}_q^V \tilde{a}_V(x), \tag{5}$$

where the coefficients $\tilde{c}_q^S$ and $\tilde{c}_q^V$ are also determined by the SU(6) quark-diquark wavefunctions, and $\tilde{a}_D(x)$ is expressed as

$$\tilde{a}_D(x) = \int [\mathrm{d}^2 \mathbf{k}_\perp] W_D(\mathrm{x}, \mathbf{k}_\perp) |\varphi(\mathrm{x}, \mathbf{k}_\perp)|^2 \qquad (\mathrm{D = S \ or \ V}) \tag{6}$$

where

$$W_D(x, \mathbf{k}_\perp) = \frac{(k^+ + m_q)^2 - \mathbf{k}_\perp^2}{(k^+ + m_q)^2 + \mathbf{k}_\perp^2}, \tag{7}$$

with $k^+ = x\mathcal{M}$ and $\mathcal{M}^2 = \frac{m_q^2 + \mathbf{k}_\perp^2}{x} + \frac{m_D^2 + \mathbf{k}_\perp^2}{1-x}$. The weight coefficients for all octet baryons, c_q^S, c_q^V, $\tilde{c}_q^S$, and $\tilde{c}_q^V$, can be also found in Table 1. We thus have all the formalism to calculate the quark distributions of the octet baryons. We should mention that the SU(3) symmetry between the octet baryons is in principle maintained, but the mass difference between different quarks and diquarks breaks the SU(3) symmetry explicitly. There is still degrees of freedom to refine the model by improving the parameters and the explicit forms of the momentum space wavefunctions.

Table 1   The quark distribution functions of octet baryons in SU(6) quark-diquark model

Baryon	q		Δq		m_q (MeV)	m_V (MeV)	m_S (MeV)
p	u	$\frac{1}{6}a_V + \frac{1}{2}a_S$	Δu	$-\frac{1}{18}\tilde{a}_V + \frac{1}{2}\tilde{a}_S$	330	800	600
(uud)	d	$\frac{1}{3}a_V$	Δd	$-\frac{1}{9}\tilde{a}_V$	330	800	600
n	u	$\frac{1}{3}a_V$	Δu	$-\frac{1}{9}\tilde{a}_V$	330	800	600
(udd)	d	$\frac{1}{6}a_V + \frac{1}{2}a_S$	Δd	$-\frac{1}{18}\tilde{a}_V + \frac{1}{2}\tilde{a}_S$	330	800	600
Σ^+	u	$\frac{1}{6}a_V + \frac{1}{2}a_S$	Δu	$-\frac{1}{18}\tilde{a}_V + \frac{1}{2}\tilde{a}_S$	330	950	750
(uus)	s	$\frac{1}{3}a_V$	Δs	$-\frac{1}{9}\tilde{a}_V$	480	800	600
Σ^0	u	$\frac{1}{12}a_V + \frac{1}{4}a_S$	Δu	$-\frac{1}{36}\tilde{a}_V + \frac{1}{4}\tilde{a}_S$	330	950	750
(uds)	d	$\frac{1}{12}a_V + \frac{1}{4}a_S$	Δd	$-\frac{1}{36}\tilde{a}_V + \frac{1}{4}\tilde{a}_S$	330	950	750
	s	$\frac{1}{3}a_V$	Δs	$-\frac{1}{9}\tilde{a}_V$	480	800	600
Σ^-	d	$\frac{1}{6}a_V + \frac{1}{2}a_S$	Δd	$-\frac{1}{18}\tilde{a}_V + \frac{1}{2}\tilde{a}_S$	330	950	750
(dds)	s	$\frac{1}{3}a_V$	Δs	$-\frac{1}{9}\tilde{a}_V$	480	800	600
Λ^0	u	$\frac{1}{4}a_V + \frac{1}{12}a_S$	Δu	$-\frac{1}{12}\tilde{a}_V + \frac{1}{12}\tilde{a}_S$	330	950	750
(uds)	d	$\frac{1}{4}a_V + \frac{1}{12}a_S$	Δd	$-\frac{1}{12}\tilde{a}_V + \frac{1}{12}\tilde{a}_S$	330	950	750
	s	$\frac{1}{3}a_S$	Δs	$\frac{1}{3}\tilde{a}_S$	480	800	600
Ξ^-	d	$\frac{1}{3}a_V$	Δd	$-\frac{1}{9}\tilde{a}_V$	330	1100	900
(dss)	s	$\frac{1}{6}a_V + \frac{1}{2}a_S$	Δs	$-\frac{1}{18}\tilde{a}_V + \frac{1}{2}\tilde{a}_S$	480	950	750
Ξ^0	u	$\frac{1}{3}a_V$	Δu	$-\frac{1}{9}\tilde{a}_V$	330	1100	900
(uss)	s	$\frac{1}{6}a_V + \frac{1}{2}a_S$	Δs	$-\frac{1}{18}\tilde{a}_V + \frac{1}{2}\tilde{a}_S$	480	950	750

2.2   The perturbative QCD counting rule analysis

We now look at the pQCD counting rule analysis of the quark distributions based on minimally connected tree graphs of hard gluon exchanges. In the region $x \to 1$ such an approach can give rigorous predictions for the behavior of distribution functions [26]. In particular, it predicts "helicity retention", which means that the helicity of a valence quark will match that of the parent nucleon. Explicitly, the quark distributions of a hadron h have been shown to satisfy the counting rule [25],

$$q_h(x) \sim (1-x)^p, \tag{8}$$

where

$$p = 2n - 1 + 2\Delta S_z. \tag{9}$$

Here n is the minimal number of the spectator quarks, and $\Delta S_z = |S_z^q - S_z^h| = 0$ or 1 for parallel or anti-parallel quark and hadron helicities, respectively [26]. Therefore the anti-parallel helicity quark distributions are suppressed by a relative factor $(1 - x)^2$, and consequently $\Delta q(x)/q(x) \to 1$ as $x \to 1$. A further input of the model, explained in detail in Ref. [26], is to retain the SU(6) ratios only for the parallel helicity distributions at large x, since in this region SU(6) is broken into $\mathrm{SU}(3)^\uparrow \times \mathrm{SU}(3)^\downarrow$. With such power-law behaviors of quark distributions, the ratio $d(x)/u(x)$ of the nucleon was predicted [39] to be $1/5$ as $x \to 1$, and this gives $F_2^n(x)/F_2^p(x) = 3/7$, which is (comparatively) close to the quark-diquark model result $1/4$ [33, 34]. From the different power-law behaviors for parallel and anti-parallel quarks, one easily finds that $\Delta q/q = 1$ as $x \to 1$ for any quark with flavor q, unless the q quark is completely negatively polarized [26]. This prediction is quite different from the quark-diquark model prediction that $\Delta d(x)/d(x) = -1/3$ as $x \to 1$ for the nucleon [27]. The most recent analysis [40, 41] of experimental data for several processes seems to support the pQCD based prediction of the unpolarized quark behaviors $d(x)/u(x) = 1/5$ at $x \to 1$, but there is still no definite test of the polarized quark behaviors $\Delta d(x)/d(x)$ since the d quark is the non-dominant quark for the proton and does not play a dominant role at large x.

The extension of pQCD based counting rule analysis to the Λ is done in Refs. [10, 11], where it is shown that the ratio $u(x)/s(x) \to 1/2$ at $x \to 1$, and this is different from the quark-diquark model prediction that $u(x)/s(x) \to 0$. However, the pQCD based analysis also predicts the positively polarized u and d quarks at large x and this is similar to the quark-diquark model prediction. It is interesting that with some adjustment to the parameterizations, the pQCD analysis can also reproduce all available data of Λ polarizations in fragmentations [10, 11, 16]. The pQCD analysis of quark distributions has also been extended to the octet baryons [12], and predictions on the Drell-Yan proceses involving hyperons have been given. This paper is purposed to study the quark distributions of all octet hyperons through fragmentations, similar to the Λ case [10, 11, 16, 17].

However, we shall adopt a different set of quark distributions from those used in Ref. [12]. The reason is that the next-to-leading order terms of every quark helicity

distributions were introduced in [12], and this is meaningful only if explicit data is available. The parameters still have large freedom and there is actually less predictive power with such parameters. Here our goal is different, since we want to predict the rough features of the quark distributions, a similar form with no adjustable parameters is enough for this purpose. Therefore we only use the leading terms for quark helicity distributions of the valence quarks

$$
\begin{aligned}
q_i^\uparrow(x) &= \frac{\tilde{A}_{q_i}}{B_3} x^{-\frac{1}{2}}(1-x)^3; \\
q_i^\downarrow(x) &= \frac{\tilde{C}_{q_i}}{B_5} x^{-\frac{1}{2}}(1-x)^5,
\end{aligned}
\tag{10}
$$

with $i = 1, 2$, where $B_n = B(1/2, n+1)$ is the β-function defined by $B(1-\alpha, n+1) = \int_0^1 x^{-\alpha}(1-x)^n dx$ for $\alpha = 1/2$, and $B_3 = 32/35$ and $B_5 = 512/693$. From (10), we obtain the valence quark normalization for quark q_i

$$
N_i = \tilde{A}_{q_i} + \tilde{C}_{q_i},
\tag{11}
$$

and the corresponding polarized distribution in the $J^p = \frac{1}{2}^+$ octet

$$
\Delta Q_i = \tilde{A}_{q_i} - \tilde{C}_{q_i},
\tag{12}
$$

which can be adjusted from $\Sigma = \Delta u + \Delta d + \Delta s \approx 0.3$, and the Bjorken sum rule $\Gamma^p - \Gamma^n = \frac{1}{6}(\Delta u - \Delta d) = \frac{1}{6} g_A/g_V \approx 0.2$, obtained in polarized DIS experiments [36]. The coefficients $\tilde{A}_{q_i}$ and $\tilde{C}_{q_i}$ ($i = 1, 2$) obtained in this way can make the ratio

$$
R_A = \frac{\tilde{A}_{q_1}}{\tilde{A}_{q_2}}
\tag{13}
$$

satisfy the $x \to 1$ behavior of $q_1^\uparrow(x)/q_2^\uparrow(x)$ for a baryon in the SU(6) quark model. However, due to the non-collinearity of the quarks, one cannot expect that the quark helicities will simply sum up to the baryon spin, as the helicity distributions measured on the light-cone are related by the Melosh-Wigner rotation to the ordinary spins of the quarks in the quark model [35]. Furthermore, the coefficients for every baryon are completely connected to each other by the SU(3) symmetry between the octet baryons, which means

$$
\begin{aligned}
u^p &= d^n = u^{\Sigma^+} = d^{\Sigma^-} = s^{\Xi^-} = s^{\Xi^0} = \tfrac{2}{3} u^\Lambda + \tfrac{4}{3} s^\Lambda = 2u^{\Sigma^0} = 2d^{\Sigma^0}; \\
d^p &= u^n = s^{\Sigma^+} = s^{\Sigma^-} = d^{\Xi^-} = u^{\Xi^0} = \tfrac{4}{3} u^\Lambda - \tfrac{1}{3} s^\Lambda = s^{\Sigma^0}.
\end{aligned}
\tag{14}
$$

11

Therefore there are actually no free parameters in this set of pQCD based quark distributions for the whole set of octet baryons, and the predictive ability of the approach is guaranteed. This set of pQCD quark distributions corresponds to a revised version of case 2 for the Λ in Ref. [11]. Of course, in this paper we are concerned by the $x \to 1$ behavior of the valence quark distributions, so that the predictions should be considered to be valid qualitatively rather than quantitatively, and the model can be improved quantitatively by adding higher order terms in the quark distributions [11, 16]. The parameters for quark distributions of octet baryons can be found from Table 2.

Table 2   The parameters for quark distributions of octet baryons in pQCD

Baryon	q_1	q_2	R_A	ΔQ_1	ΔQ_2	$\tilde{A}_{q_1}$	$\tilde{C}_{q_1}$	$\tilde{A}_{q_2}$	$\tilde{C}_{q_2}$
p	u	d	5	0.75	-0.45	1.375	0.625	0.275	0.725
n	d	u	5	0.75	-0.45	1.375	0.625	0.275	0.725
Σ^+	u	s	5	0.75	-0.45	1.375	0.625	0.275	0.725
Σ^0	u(d)	s	$\frac{5}{2}$	0.375	-0.45	0.6875	0.3125	0.275	0.725
Σ^-	d	s	5	0.75	-0.45	1.375	0.625	0.275	0.725
Λ^0	s	u(d)	2	0.65	-0.175	0.825	0.175	0.4125	0.5875
Ξ^-	s	d	5	0.75	-0.45	1.375	0.625	0.275	0.725
Ξ^0	s	u	5	0.75	-0.45	1.375	0.625	0.275	0.725

3   Baryon polarizations in e^+e^--annihilation at two energies

In the standard model of electroweak interactions, the produced quarks and anti-quarks should be polarized in the unpolarized e^+e^--annihilation process due to the parity-violating coupling of the fermions, and this leads to the polarizations of the baryons (antibaryons) from the decays of the quarks (antiquarks). Therefore we can study the polarized quark to hadron fragmentations by the semi-inclusive production of hadrons in e^+e^--annihilation [1, 2, 7, 8, 11, 18].

The polarizations of the initial quarks from e^+e^--annihilation are given by

$$P_q = -\frac{A_q(1 + \cos^2\theta) + B_q\cos\theta}{C_q(1 + \cos^2\theta) + D_q\cos\theta}, \tag{15}$$

where

$$A_q = 2\chi_2(v_e^2 + a_e^2)v_q a_q - 2e_q\chi_1 a_q v_e, \tag{16}$$

$$B_q = 4\chi_2 v_e a_e(v_q^2 + a_q^2) - 4e_q\chi_1 a_e v_q, \tag{17}$$

$$C_q = e_q^2 - 2\chi_1 v_e v_q e_q + \chi_2(a_e^2 + v_e^2)(a_q^2 + v_q^2), \tag{18}$$

$$D_q = 8\chi_2 a_e a_q v_e v_q - 4\chi_1 a_e a_q e_q, \tag{19}$$

in which

$$\chi_1 = \frac{1}{16\sin^2\theta_W\cos^2\theta_W}\frac{s(s - M_Z^2)}{(s - M_Z^2)^2 + M_Z^2\Gamma_Z^2}, \tag{20}$$

$$\chi_2 = \frac{1}{256\sin^4\theta_W\cos^4\theta_W}\frac{s^2}{(s - M_Z^2)^2 + M_Z^2\Gamma_Z^2}, \tag{21}$$

$$a_e = -1 \tag{22}$$

$$v_e = -1 + 4\sin^2\theta_W \tag{23}$$

$$a_q = 2T_{3q}, \tag{24}$$

$$v_q = 2T_{3q} - 4e_q\sin^2\theta_W, \tag{25}$$

where $T_{3q} = 1/2$ for u, c, while $T_{3q} = -1/2$ for d, s, b quarks, $N_c = 3$ is the color number, e_q is the charge of the quark in units of the proton charge, θ is the angle between the outgoing quark and the incoming electron, θ_W is the Weinberg angle with $sin^2\theta_W = 0.2312$, and $M_Z = 91.187$ GeV and $\Gamma_Z = 2.49$ GeV are the mass and width of Z^0 [42]. Averaging over θ for Eq. (15), one obtains $P_q = -0.67$ for $q = u$, c, $P_q = -0.94$ for $q = d$, s, and b, and $r_{d/u} = C_d/C_u = 1.29$ at the Z-pole, i.e., the LEP I energy $\sqrt{s} = 91.187$ GeV. However, at the LEP II energy $\sqrt{s} = 200$ GeV, we can find that the γ^*/Z^0 interference should contribute since the terms involving χ_1 do not vanish. One obtains, $P_q = -0.29$ for $q = u$, c, $P_q = -0.71$ for $q = d$, s, and b, and $r_{d/u} = 0.61$, which are different from those at LEP I. We notice that the absolute value of P_q decreases with the energy square s from LEP I to LEP II, as a result of non-zero χ_1.

From the cross section formulae [2, 11] for the unpolarized and polarized hadron h production, we can write the formula for the hadron h polarization

$$P_h(\theta) = -\frac{\sum\limits_{q}\left\{A_q(1+\cos^2\theta)[\Delta D_q^h(z) - \Delta D_{\bar{q}}^h(z)] + B_q\cos\theta[\Delta D_q^h(z) + \Delta D_{\bar{q}}^h(z)]\right\}}{\sum\limits_{q}\left\{C_q(1+\cos^2\theta)[D_q^h(z) + D_{\bar{q}}^h(z)] + D_q\cos\theta[D_q^h(z) + D_{\bar{q}}^h(z)]\right\}}.$$

(26)

By averaging over θ we obtain

$$P_h = -\frac{\sum\limits_{q}A_q[\Delta D_q^h(z) - \Delta D_{\bar{q}}^h(z)]}{\sum\limits_{q}C_q[D_q^h(z) + D_{\bar{q}}^h(z)]}.$$

(27)

We now present in Fig. 1 the calculated hadron polarizations for the octet baryons by adopting the Ansatz of Eq. (1) connecting the fragmentation functions with the quark distributions, in both the quark-diquark model and the pQCD based analysis presented in the previous section.

There have been measurements of the Λ-polarization near the Z-pole [19, 20, 21], i.e., at LEP I energy, and we have already shown that the predictions of the two models are compatible with the data [11]. At LEP II energy, the predictions for the Λ in the two models are also qualitatively similar, as can be seen from Fig. 1(a). Therefore in order to distinguish between the two models we need high precision measurements at large z. For Ξ^0 and Ξ^-, the predictions for the polarizations in the two models are also close to each other, and a clear distinction between the two models is not easy, although there is some difference between the $z \to 1$ behavior for Ξ^0 in both models. However, we notice from Fig. 1(b)-(d) that the predictions for Σ's are quite different in the two models, and it is possible to distinguish between them by the qualitative behavior of the Σ polarizations in the medium to large z region. This can be easily understood since the Σ's have the most significant difference in the flavor and spin structure between the two models in the medium to large x region [12]. It is also interesting that our predictions for the Σ polarizations are in an opposite direction to the predictions by Liu and Liang, based on Monte-Carlo event generators of two different pictures of quark polarizations inside the Λ without a physical mechanism for the z-dependence, as can be seen by comparing our Fig. 1(c)-(d) with their Fig. 10 [18].
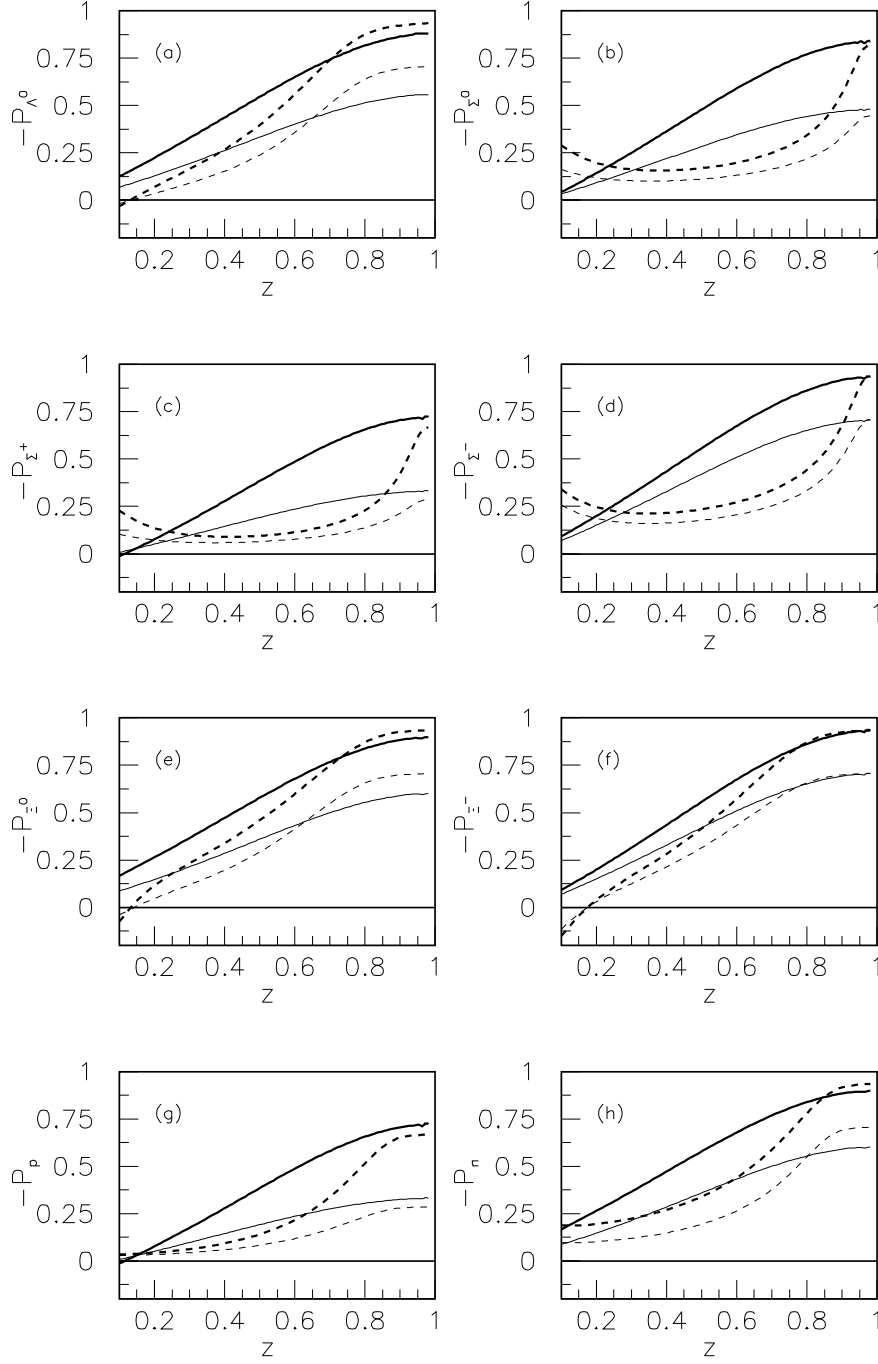
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Figure 1: The prediction of the longitudinal hadron polarizations for the octet baryons in e^+e^--annihilation at two energies: LEP I at Z resonance $\sqrt{s} \approx 91$ GeV (thick curves) and LEP II at $\sqrt{s} \approx 200$ GeV (thin curves), with input fragmentation functions adopting the Ansatz Eq. (1) from valence quark distributions in the pQCD based analysis (solid curves) and the quark-diquark model (dashed curves).

The different trends for the polarizations of Σ's can be easily understood. The contributions of u, d and s quarks to the polarization of the produced hadron are of the same order as can be seen from the calculated ratio $r_{d/u}$ in e^+e^--annihilation. In the pQCD based analysis, both the s quark and the u (d) quarks for Σ^+ (Σ^-) are positively polarized inside the Σ's at large x, therefore the spin transfer from the initial quarks to the produced hadron is positive. In the quark-diquark model, the s quarks inside Σ's are negatively polarized, and their distribution is big in the medium to large x region; but the u and d quarks are positively polarized and dominant at $x \to 1$, as can be seen from Figs. 3-4 in Ref. [12], and therefore the contribution from the s quark causes a decrease in the spin transfer from all initial quarks in the medium to large z region. However, in the analysis based on Monte-Carlo event generators [18], the s quark contribution to the hadron fragmentation is dominant at $z > 0.5$ so that the spin of the produced Σ's comes from the initial s quarks, which are negatively polarized inside Σ's in their inputs, therefore the produced Σ's should be negatively polarized in comparison to the quark polarization. We know that the $\Sigma^\pm$ polarizations can be measured in experiments [30] and the $\Sigma^\pm$ fragmentations can also be measured in e^+e^--annihilation [43]. Therefore there should be no problem to measure the $\Sigma^\pm$ in e^+e^--annihilation with the available experimental technique, and this can provide a sensitive test of the above different predictions.

Nevertheless, in both the pQCD based analysis and the quark-diquark model, the s quarks inside Ξ's are positively polarized, and they contribute dominantly to the polarizations of the produced Ξ's at large z. This is also true in the Monte-Carlo analysis, and we thus arrive at the same conclusion as Liu and Liang [18] that there is little theoretical uncertainty to predict the Ξ polarizations at large z, as can be seen from our Fig. 1(e)-(f) and Fig. 10 in [18]. But there are still quantitative difference in the predictions and high precision measurements can tell the difference. This implies that the polarizations of Σ's produced in e^+e^--annihilation can provide clearer information to distinguish between the quark contributions to the hadron fragmentation from different flavors than the Ξ's, therefore the Σ polarizations in e^+e^--annihilation deserve experimental attention.

4 Baryon polarizations in polarized charged lepton DIS process

We now look at the spin transfers for a hadron h production in polarized charged lepton DIS process. For a longitudinally polarized charged lepton beam and an unpolarized nucleon target, the longitudinal spin transfer to the fragmented hadron h is given in the quark parton model by [4]

$$A^h(x,z) = \frac{\sum\limits_q e_q^2[q^N(x,Q^2)\Delta D_q^h(z,Q^2) + (q \to \overline{q})]}{\sum\limits_q e_q^2[q^N(x,Q^2)D_q^h(z,Q^2) + (q \to \overline{q})]} \ . \tag{28}$$

Here $y = \nu/E$, $x = Q^2/2M_N\nu$, and $z = E_h/\nu$, where $q^2 = -Q^2$ is the squared four-momentum transfer of the virtual photon, M_N is the proton mass, and ν, E, and E_h are the energies of the virtual photon, the target nucleon, and the produced hadron h respectively, in the target rest frame; $q^N(x,Q^2)$ is the quark distribution for the quark q in the target nucleon, $D_q^h(z,Q^2)$ is the fragmentation function for h production from quark q, $\Delta D_q^h(z,Q^2)$ is the corresponding longitudinal spin-dependent fragmentation function, and e_q is the quark charge in units of the elementary charge e. For $\overline{h}$ production the spin transfer $A^{\overline{h}}(x,z)$ is obtained from Eq. (28) by replacing hadron h by anti-hadron $\overline{h}$. The h and $\overline{h}$ fragmentation functions are related since we can safely assume matter-antimatter symmetry, $i.e.$, $D_{q,\overline{q}}^h(z) = D_{\overline{q},q}^{\overline{h}}(z)$ and similarly for $\Delta D_{q,\overline{q}}^h(z)$.

Recently, the HERMES Collaboration at DESY reported the preliminary result of the longitudinal spin transfer to the Λ in polarized positron DIS on the proton [22]. The E665 Collaboration at FNAL also measured the Λ and $\overline{\Lambda}$ spin transfers from muon DIS [23], and they observed very different behaviour for Λ and $\overline{\Lambda}$ polarizations, which might be related to the quark/antiquark asymmetry of the nucleon sea either in the fragmentation functions or in the distribution functions of the target [16, 17]. The available data are consistent with both the quark-diquark model and the pQCD based analysis for the quark to Λ fragmentation functions [10, 16, 17], and this again supports the use of the Gribov-Lipatov relation as an Ansatz to connect fragmentation functions with distribution functions. In this section we only discuss the contribution

from valence quarks in the fragmentation functions, and therefore the predictions should be only reasonable qualitatively at large z.

We extend our analysis of the spin transfers for the octet baryons and present our results in Figs. 2-3, where the spin transfers for baryons and anti-baryons are given respectively. There is no much difference between the two figures since the integrated x range of the target quark distributions is $0.02 \to 0.4$ where both quarks and antiquarks are important. From Fig. 2 and Fig. 3 we notice that the predictions of the spin transfers are very similar between the pQCD based analysis and the quark-diquark model for most baryons and anti-baryons, except for Ξ^0 and n where the spin transfers might be negative at medium z in the quark-diquark model. This can be easily understood since the dominant fragmentation chains contributing to this behavior are $u \to \Xi^0$ and $u \to n$ as the u quarks should be negatively polarized at $x \to 1$ inside Ξ^0 and n, and the square charge factor of the u quarks is 4/9 compared to 1/9 for the d quarks. Also the larger number of u quarks inside the proton target amplifies this negative contribution. We propose to measure the Ξ^0 transfer in the polarized DIS process to check the two different predictions, as the experimental technique for measuring Ξ^0 polarization is also well developed [31].

5   Baryon polarizations in neutrino/antineutrino DIS process

One advantage of neutrino (antineutrino) process is that the scattering of a neutrino beam on a hadronic target provides *a source of polarized quarks with specific flavor structure*, and this particular property makes the neutrino (antineutrino) process an ideal laboratory to study the flavor-dependence of quark to hadron fragmentation functions, especially in the polarized case [9]. For the production of any hadron h from neutrino and antineutrino DIS processes, the longitudinal polarizations of h in its momentum direction, for h in the current fragmentation region can be expressed
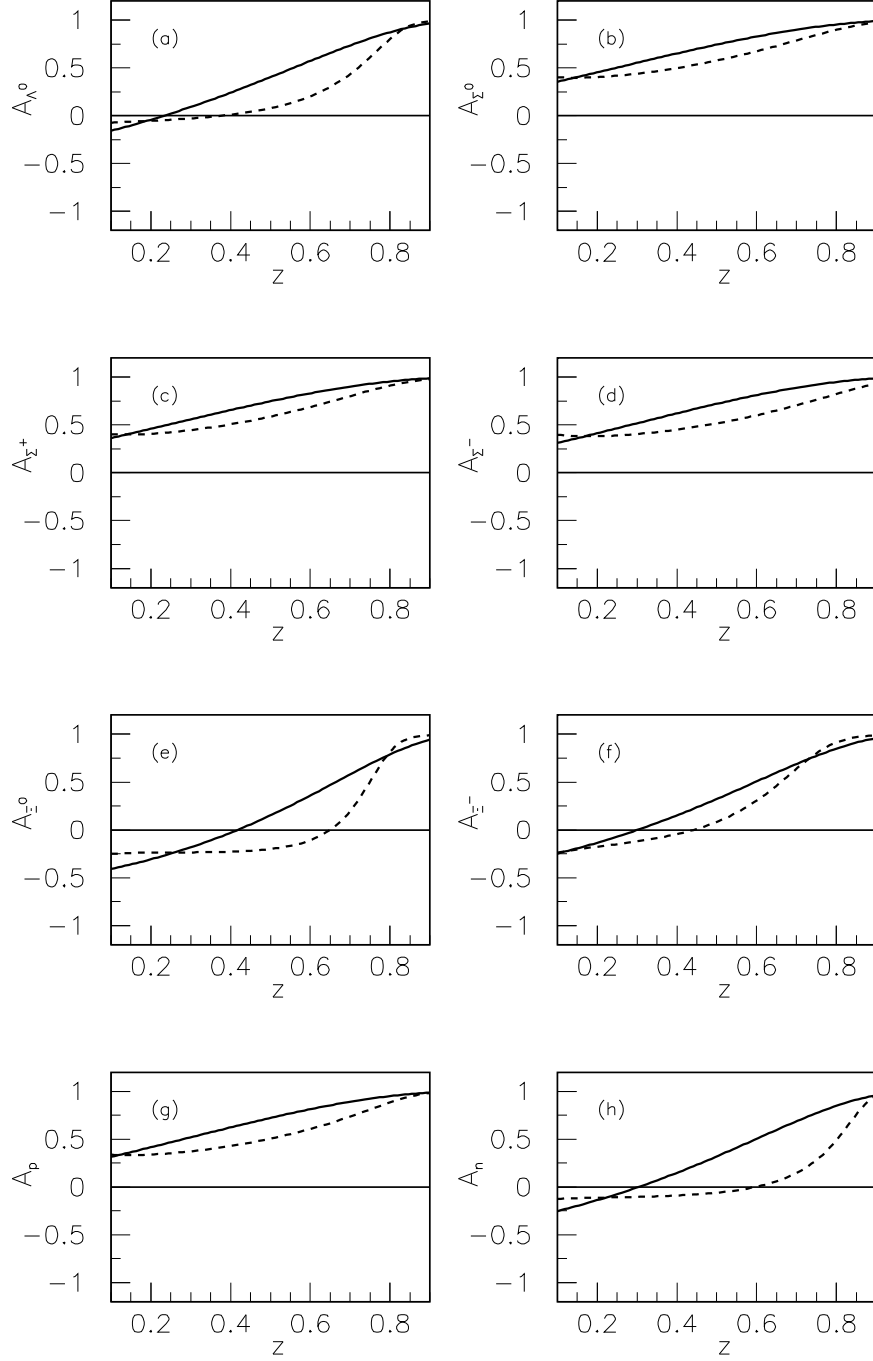
Figure 2: The predictions of the z-dependence for the *hadron* spin transfer in polarized charged lepton DIS process for the octet baryons. We adopt the CTEQ5 set 1 quark distributions [44] for the target proton at $Q^2 = 2.5$ GeV^2 with the Bjorken variable x integrated over $0.02 \rightarrow 0.4$. The corresponding input fragmentation functions adopt the Ansatz Eq. (1) from valence quark distributions in the pQCD based analysis (solid curves) and the quark-diquark model (dashed curves).
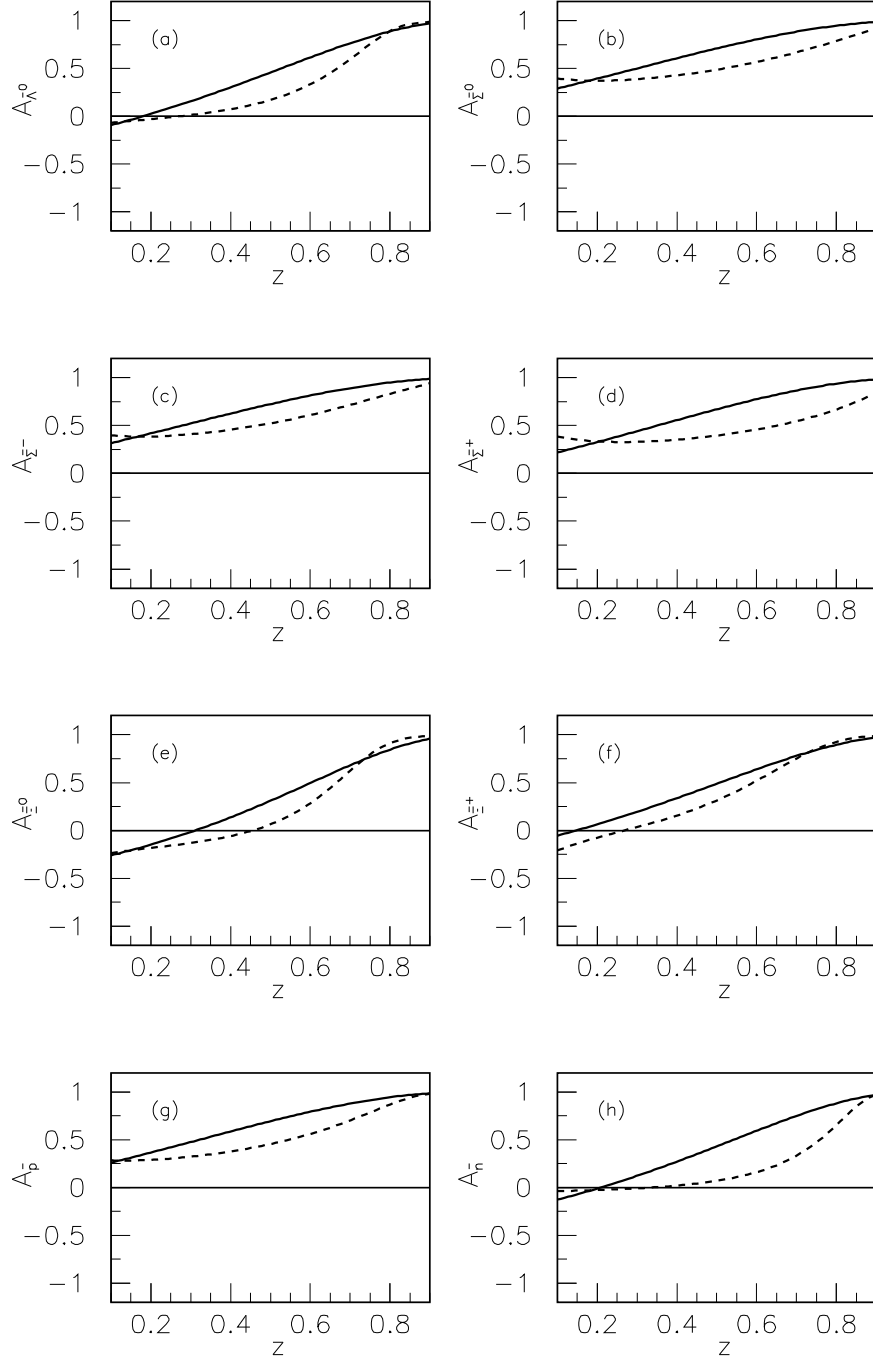
Figure 3: The predictions of the *z*-dependence for the *anti-hadron* spin transfer in polarized charged lepton DIS process for the octet anti-baryons. The others are the same as Fig. 2.

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as [16],

$$P_\nu^h(x, y, z) = -\frac{[d(x) + \varpi s(x)]\Delta D_u^h(z) - (1-y)^2 \overline{u}(x)[\Delta D_{\overline{d}}^h(z) + \varpi \Delta D_{\overline{s}}^h(z)]}{[d(x) + \varpi s(x)]D_u^h(z) + (1-y)^2 \overline{u}(x)[D_{\overline{d}}^h(z) + \varpi D_{\overline{s}}^h(z)]} \ , \quad (29)$$

$$P_{\overline{\nu}}^h(x, y, z) = -\frac{(1-y)^2 u(x)[\Delta D_d^h(z) + \varpi \Delta D_s^h(z)] - [\overline{d}(x) + \varpi \overline{s}(x)]\Delta D_{\overline{u}}^h(z)}{(1-y)^2 u(x)[D_d^h(z) + \varpi D_s^h(z)] + [\overline{d}(x) + \varpi \overline{s}(x)]D_{\overline{u}}^h(z)} \ , \quad (30)$$

where the terms with the factor $\varpi = \sin^2\theta_c/\cos^2\theta_c$ (θ_c is the Cabibbo angle) represent Cabibbo suppressed contributions. We have neglected the charm contributions both in the target and in hadron h. The detailed x-, y-, and z- dependencies can provide more information concerning the various fragmentation functions. As a special case, the y-dependence can be simply removed by integrating over the appropriate energy range and we can also integrate the x-dependence to increase the statistics in experimental data treatments.

In the Λ case there is an interchange symmetry between the u and d quarks: $u \leftrightarrow d$, which in general is not present for other hadrons. After considering the symmetries between different quark to hadron and anti-hadron fragmentation functions [9], there should be 8 independent fragmentation functions which can be measured in neutrino (antineutrino) DIS process for each hadron h,

$$D_u^h, \quad D_{\overline{u}}^h, \quad D_d^h + \varpi D_s^h, \quad D_{\overline{d}}^h + \varpi D_{\overline{s}}^h, \quad (31)$$

and

$$\Delta D_u^h, \quad \Delta D_{\overline{u}}^h, \quad \Delta D_d^h + \varpi \Delta D_s^h, \quad \Delta D_{\overline{d}}^h + \varpi \Delta D_{\overline{s}}^h. \quad (32)$$

Different combinations of unpolarized and polarized h and $\overline{h}$ productions in neutrino and antineutrino processes, and choices of specific kinematics regions with different x, y, and z, can measure the above fragmentation functions efficiently. Unlike the Λ case where the $u \leftrightarrow d$ symmetry can be used [9, 16], it is not possible to separate the d and s quark fragmentation functions for any hadron h due to the Cabibbo mixing. However, in combination with the flavor dependence of fragmentation functions in e^+e^--annihilation and polarized charged lepton DIS process, it should be possible to extract the various d and s quark fragmentation functions, provided the accuracy of
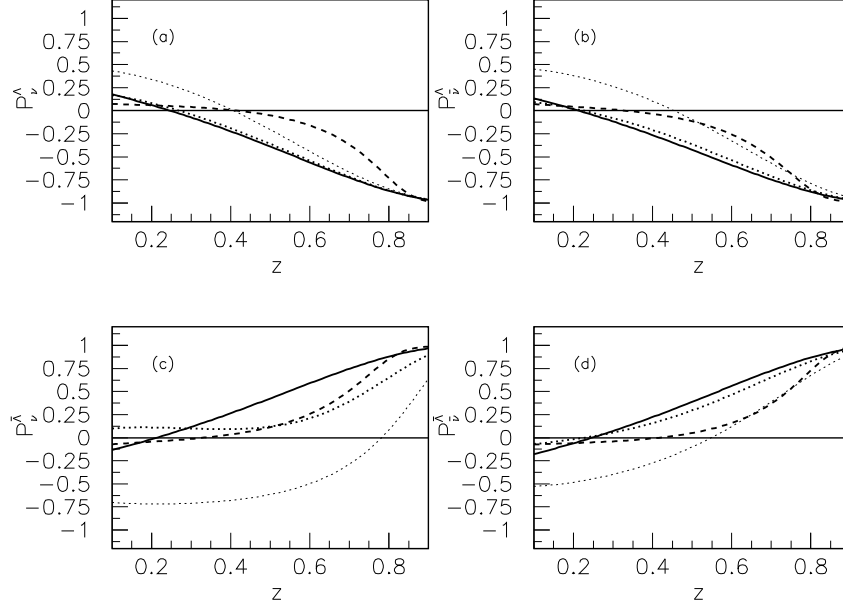
Figure 4: The predictions of z-dependence for the hadron and anti-hadron polarizations of Λ in the neutrino (antineutrino) DIS process. The solid and dashed curves are results with input fragmentation functions adopting the Ansatz Eq. (1) from valence quark distributions in the pQCD based analysis (solid curves) and the quark-diquark model (dashed curves), and the dotted curves are the results for the pQCD based analysis of valence quarks with scenario I of asymmetric quark-antiquark sea (thin dotted curves) and scenario II of symmetric quark-antiquark sea (think dotted curves) in Ref. [16]. We adopt the CTEQ5 set 1 quark distributions [44] for the target proton at $Q^2 = 2.5$ GeV^2 with the Bjorken variable x integrated over $0.02 \rightarrow 0.4$ and y integrated over $0 \rightarrow 1$.

the data is high enough. Another advantage of the neutrino (antineutrino) processes is that the antiquark to hadron fragmentation can also be conveniently extracted, and this can be compared to specific predictions concerning the antiquark polarizations inside baryons.

In Figs. 4-11 we present our predictions for the hadron and anti-hadron polarizations of the octet baryons in neutrino and anti-neutrino DIS processes. Some precision data on Λ and $\overline{\Lambda}$ production have been taken by the NOMAD neutrino beam experiment [24], and our predictions for the Λ polarization in both the pQCD based analysis and the quark-diquark model, as presented in Fig. 4(a), has been proved to be supported by the preliminary data. Notice that another work [5] predicted quite different
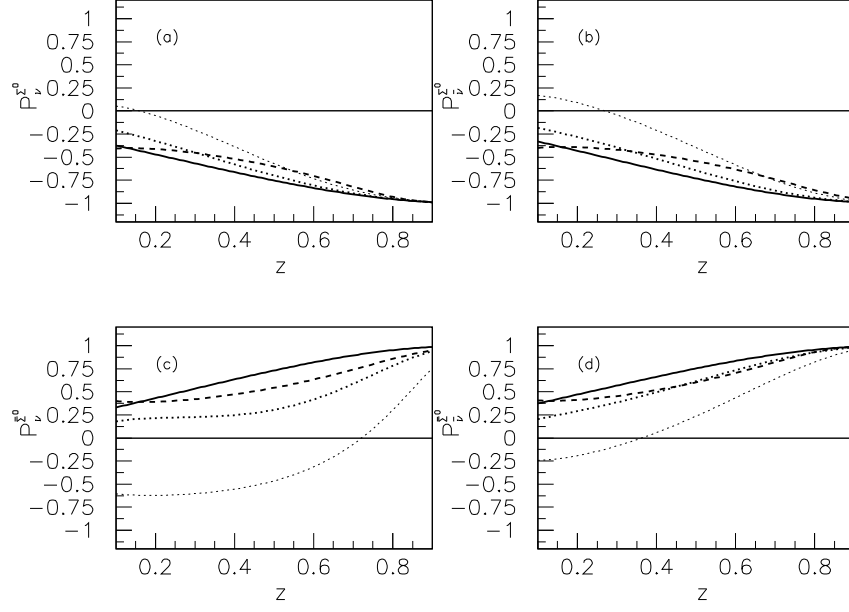
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Figure 5: The same as Fig. 4, but for predictions of z-dependence for the hadron and anti-hadron polarizations of Σ^0 in the neutrino (antineutrino) DIS process.
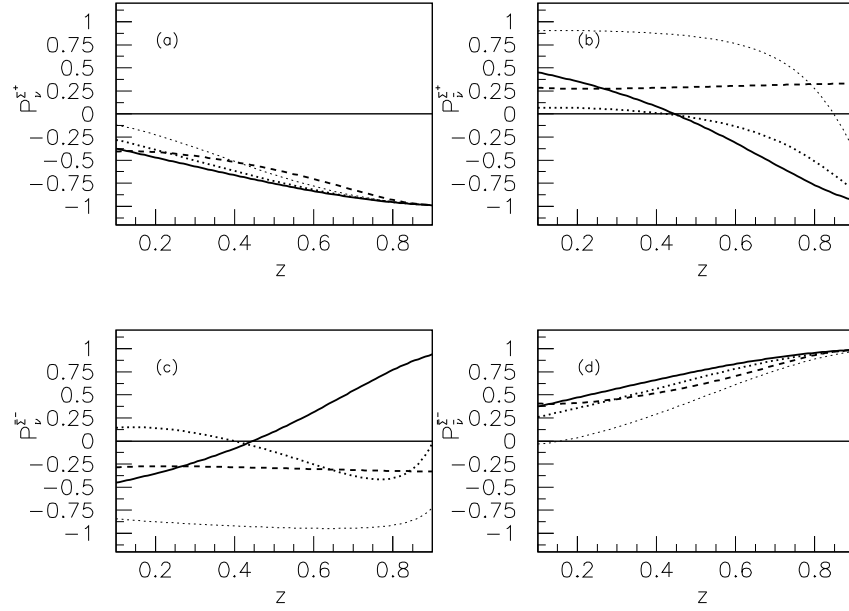

Figure 6: The same as Fig. 4, but for predictions of z-dependence for the hadron and anti-hadron polarizations of Σ^+ in the neutrino (antineutrino) DIS process.
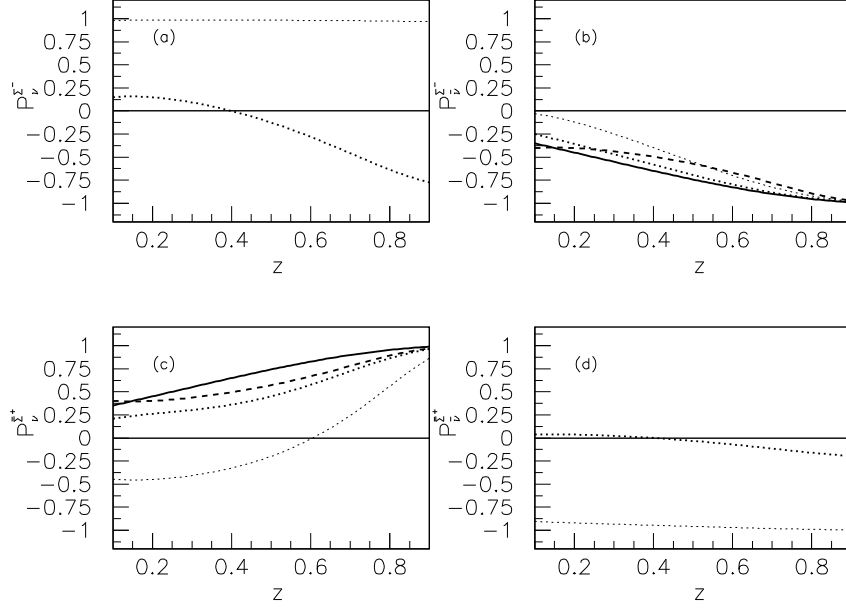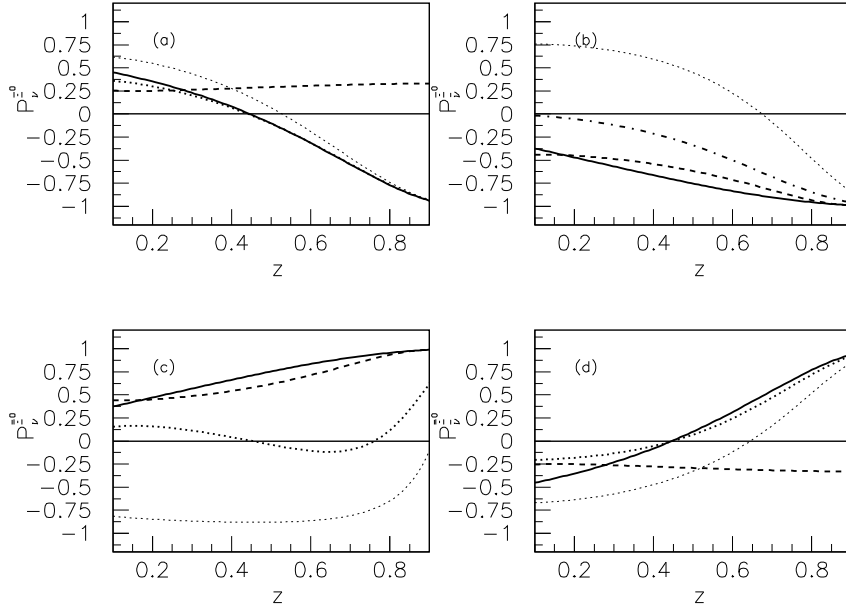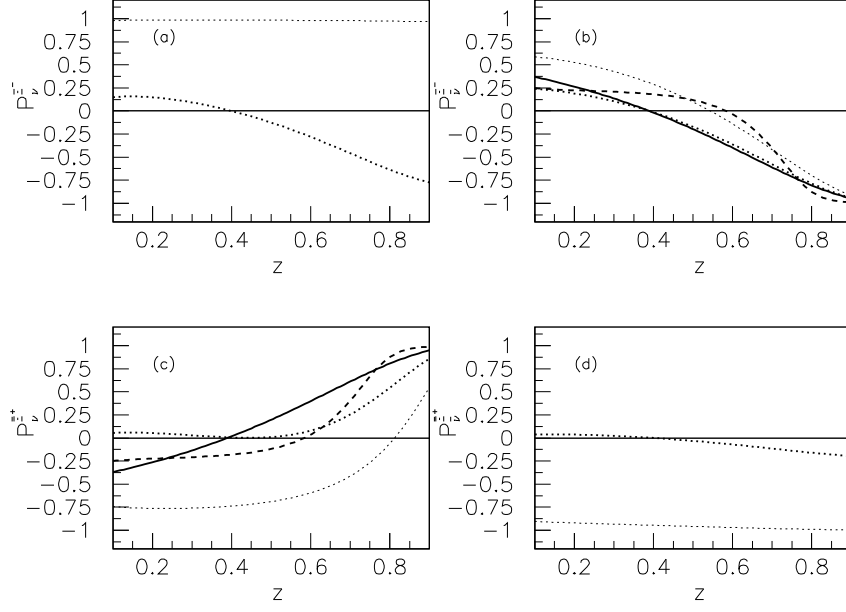
Figure 7: The same as Fig. 4, but for predictions of z-dependence for the hadron and anti-hadron polarizations of Σ^- in the neutrino (antineutrino) DIS process.

Figure 8: The same as Fig. 4, but for predictions of z-dependence for the hadron and anti-hadron polarizations of Ξ^0 in the neutrino (antineutrino) DIS process.

Figure 9: The same as Fig. 4, but for predictions of z-dependence for the hadron and anti-hadron polarizations of Ξ^- in the neutrino (antineutrino) DIS process.
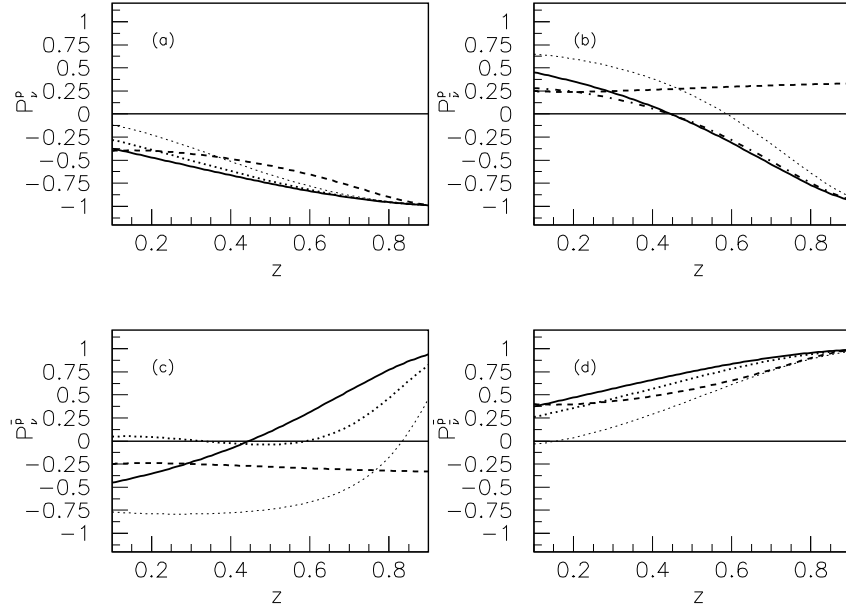

Figure 10: The same as Fig. 4, but for predictions of z-dependence for the hadron and anti-hadron polarizations of p in the neutrino (antineutrino) DIS process.
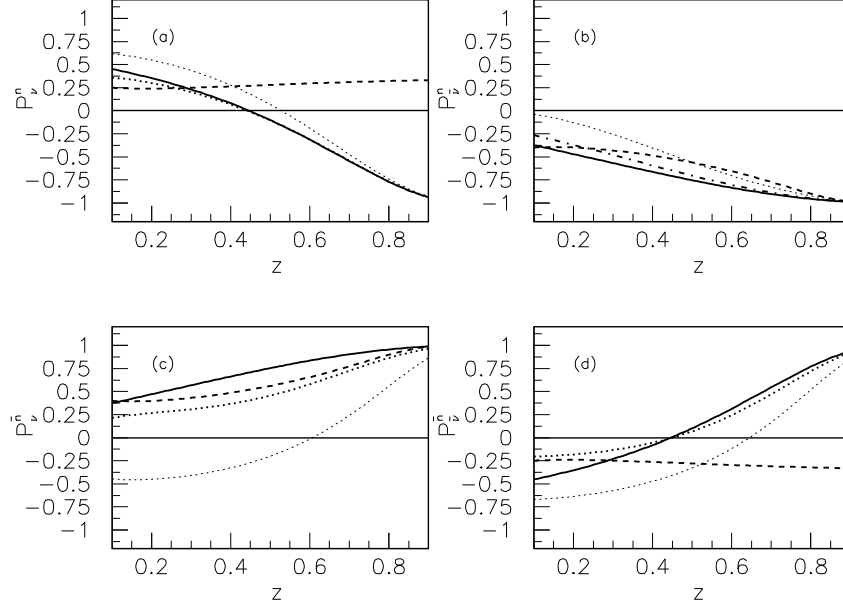
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Figure 11: The same as Fig. 4, but for predictions of z-dependence for the hadron and anti-hadron polarizations of n in the neutrino (antineutrino) DIS process.

Λ polarization compared to ours. Thus our knowledge of the quark to Λ fragmentation functions is improving. In principle, the polarizations for $\Sigma^{\pm}$, Ξ^0, and Ξ^- and their anti-hadron partners can be also measured by the NOMAD collaboration, therefore we can systematically study the flavor decomposition of various quark to octet baryon fragmentation functions. This will enrich our knowledge on the fragmentation functions and the detailed quark structure of octet baryons.

Now we look only at the contributions from the valence quarks, shown in Figs. 4-11 as solid curves for the pQCD based analysis and dashed curves for the quark-diquark model. We find that the Σ^+ and Ξ^0 have significant different predictions between the two models, as can be seen from Fig. 6(b) and (c) for Σ^+, and from Fig. 8(a) and (d) for Ξ^0. The difference can be understood as follows. For the Σ^+ production in $\overline{\nu}$ DIS, we can see from Eq. (30) that only the d and s quarks contribute, whereas inside Σ^+ only the s valence quark contributes. The s quark is positive polarized at large x in the pQCD based analysis, whereas it is negatively polarized in the quark-diquark model. This gives opposite trends of the Σ^+ polarizations at large z in the two models.

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This discussion can also be extended to $\overline{\Sigma}^-$ in ν DIS as shown in Fig. 6(c). For the Ξ^0 production in ν DIS, as can be seen from Eq. (29), only the u quarks contribute and the u valence quarks inside Ξ^0 are positively polarized in the pQCD based analysis at large x whereas it is negatively polarized in the quark-diquark model. This gives different trends of the Ξ^0 polarizations at large z between the two models, and a similar discussion applies to $\overline{\Xi}^0$ production in $\overline{\nu}$ DIS as shown in Fig. 8(d). Thus the Σ^+ and Ξ^0 polarizations in neutrino (antineutrino) DIS process can test different predictions between the pQCD based analysis and the quark-diquark model.

We now look at Fig. 10(b),(c) and Fig. 11(a), (d), and find that a similar discussion also applies to the nucleon. This means that measuring the nucleon polarizations in the neutrino (antineutrino) DIS process, for example p polarization in $\overline{\nu}$ DIS, can provide a good test for the different predictions of $\Delta d/d = -1/3$ at large x in the quark-diquark model [27] and $\Delta d/d = 1$ at $x \to 1$ in the pQCD based analysis [26].

We also notice that there are no valence quark contributions to Σ^- and Ξ^- productions in ν DIS process, and similarly for the productions of their anti-baryon partners, $\overline{\Sigma}^+$ and $\overline{\Xi}^+$, in $\overline{\nu}$ DIS process. This means that the above channels are the most suitable in order to study the contributions from antiquarks to the fragmentation functions. In order to show the sensitivity to the sea quark content of the octet baryons, we adopt the two scenarios of sea quark distributions in Ref. [16] for the Λ and simply assume that the sea is the same for all octet baryons. This assumption is surely not correct, but our knowledge of the sea quark distributions inside hyperons is rather poor at the moment. From another point of view, the Gribov-Lipatov relation Eq. (1) should be only valid at large z, and we should consider our method as a phenomenological way to parameterize the quark (antiquark) to baryon fragmentations in the small z region. Therefore we should not rely strongly on the predictions for the sea quark content of the hyperons, and our purpose is only to show that the results are rather sensitive to different scenarios of the sea quarks. Scenario I of the sea quarks corresponds to asymmetric quark-antiquark helicity distributions, and scenario II corresponds to a symmetric case, and the predictions including the sea contributions together with the valence quarks in the pQCD based analysis are shown as dotted curves (thin curves for scenario I and thick curves for scenario II) in Figs. 4-

11. From Figs. 7(a) and 9(a) we find that the Σ^- and Ξ^- polarizations are rather sensitive to the different scenarios and therefore a measure of these polarizations in ν DIS process can provide important information concerning the contributions from antiquark to hyperon fragmentations. We also notice that the sea contributions also play an important role in hyperon productions of neutrino (antineutrino) DIS process, as can be seen from Figs. 4-11. Thus neutrino (antineutrino) DIS process is a sensitive place to study the sea quark content of hyperons, although this requires high precision data.

6 Summary and Conclusion

In this paper we systematically extend our study of the spin and flavor structure of the Λ, to all other hyperons of the octet baryons, by considering quark fragmentation in three different processes. The predictions of the Λ longitudinal polarizations in both the quark-diquark model and pQCD based analysis, have been proved to be supported by the available data for Λ production in the three processes: e^+e^--annihilation, polarized charged lepton DIS, and neutrino (antineutrino) DIS. We presented in this paper the predictions of the hyperon longitudinal polarizations for the octet baryons obtained by fragmentation in the above three processes, and suggested sensitive tests to check the different predictions. We find that the polarization of Σ hyperons in e^+e^- annihilation provides a new direction to test different predictions. The Ξ^0 polarization in polarized charged lepton DIS process on the proton target can also test the different predictions between the pQCD based analysis and the quark-diquark model. The Σ^+ and Ξ^0 polarizations in neutrino (antineutrino) DIS process can test the different predictions concerning the valence structure of the hyperons, whereas Σ^- and Ξ^- polarizations are suitable to study the antiquark to hyperon fragmentations. The predictions of this paper are supposed to be valid qualitatively rather than quantitatively, and the difference in the predictions can be understood by clear physical pictures which can be tested explicitly by various methods. We expect that systematic studies on the various hyperon fragmentations, both theoretical and experimental, will enrich our knowledge of the quark to hadron fragmentations and of

the quark structure of the octet baryons.

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